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Active Detection of Shielded SNM with 60-keV Neutrons

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***Abstract*—Fissile materials, e.g. ^{235}U and ^{239}Pu, can be detected non-invasively by active neutron interrogation. A unique characteristic of fissile material exposed to neutrons is the prompt emission of high-energy (fast) fission neutrons. One promising mode of operation subjects the object to a beam of medium-energy (epithermal) neutrons, generated by a proton beam impinging on a Li target. The emergence of fast secondary neutrons then clearly indicates the presence of fissile material. Our interrogation system comprises a low-dose 60-keV neutron generator (5×10^6/s), and a 1 m^2 array of scintillators for fast neutron detection. Preliminary experimental results demonstrate the detectability of small quantities (370 g) of HEU shielded by steel (200 g/cm^2) or plywood (30 g/cm^2), with a typical measurement time of 1 min.**

***Index Terms*—detectors, inspection, neutron beams, neutron sources**

I. Introduction

RELIABLE and efficient tools are needed for detecting the presence of hidden fissile materials at border checkpoints and during search operations. Passive means of inspection rely on the detection of the spontaneous decay products (mainly neutrons and photons) of fissile materials. This is a safe and simple method, however a low signal rate (especially for ^{235}U) may preclude detection. Active methods involve a probing beam of neutrons or photons and the detection of characteristic particle emissions. In principle, any amount of shielding can be penetrated with adequate source strength, but at potentially high cost and complexity.

Here we describe an active system based on an interrogating beam of low-energy (60-keV) neutrons, which may induce fission in ^{235}U and ^{239}Pu, but not in ^{232}Th and only weakly in ^{238}U [1,2]. The prompt fission neutrons have a typical energy of ~ 1-MeV and are synchronously detected and discriminated from the 60-keV source neutrons and associated photons. Hence the presence of fast neutrons correlated with the source provides a clear signature for SNM. The efficacy of the method strongly depends on the type and thickness of the shielding material. Hydrogenous cargo tends to moderate and absorb both the incident and outgoing neutrons, severely degrading the signal even for fairly thin shielding. Non-hydrogenous shielding on the other hand can be penetrated with ease while the escaping fission neutrons suffer only little energy degradation.

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II. Neutron Source

The neutron source was custom designed and built by AccSys [3], Inc., and is optimized for small weight and power consumption. At its heart lies a compact radiofrequency quadrupole (RFQ) that accelerates protons produced by an electron cyclotron resonance (ECR) source. Its specifications are summarized in Table 1.

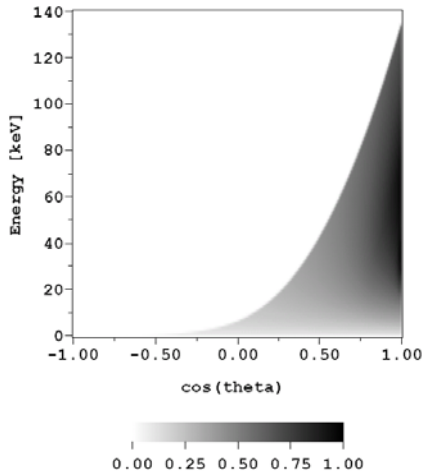

Figure 1: Calculated neutron angle-energy distribution from ^{7}Li(p,n)^{7}Be. The protons of energy 1.93 MeV are incident normally on a thick Li target.

The ^{7}Li(p,n)^{7}Be reaction has a threshold of 1.88 MeV. Its cross section rises quickly and reaches a plateau of ~ 200 mb at 1.91 MeV. In the center-of-mass frame the neutron distribution is nearly isotropic near threshold, but strongly forward directed in the laboratory frame. Fig.1 shows the calculated neutron angle-energy distribution using the tables published by Liskien et al. [4]. The target was assumed to be thick, meaning the ionization energy loss was > 50 keV. The thickness of the actual Li target was about twice that at 1 mg/cm^2, deposited on a solid Ag backing. After several hundred hours of running, we noticed substantial blistering of

the target due to hydrogen gas build-up. We plan to remedy this in future with a sintered Ag backing to increase gas diffusion.

TABLE I
NEUTRON SOURCE SPECIFICATIONS

Accelerated Ions	Protons
Reaction	^{7}Li(p,n)^{7}Be
Neutron Yield	5×10^{6}/s
Output Beam Energy	1.93 MeV
Average Proton Current	1 μA
Repetition Rate	100 Hz
Pulse Width	30 μs
Average Beam Power	2 W
Instrument Weight	230 kg in 2 boxes
Target	Natural Li on Ag backing, 1 mg/cm^2
Radiation Dose to Cargo	~ 1mRem/hr at 2.5 m

III. BACKGROUNDS

The 60-keV neutron generator also produces a small number of fast neutrons via proton capture on ^{7}Li. A single hard gamma of 14 MeV or 17 MeV is emitted in this reaction. Subsequent photonuclear absorption in surrounding materials may create additional fast neutrons. Another important background source is ^{7}Li(p,α)^{4}He followed by ^{4}He(^{7}Li,n)^{10}B. Based on published cross sections [5,6,7,8], we estimate a contamination of 10^{-5} fast neutrons per epithermal neutron from above reactions. Both backgrounds are minimized by employing a Li layer that slows protons to just below the ^{7}Li(p,n)^{7}Be threshold.

A natural background of fast neutrons is produced by interactions of solar and galactic protons and their secondaries in the atmosphere and on the ground. The flux depends on location and solar activity, a typical value is 30/m^{2}s at sea level. With a pulsed neutron generator this background can be gated out to some extent.

A large number of gammas correlated with the generator is also present, mainly from ^{7}Li(p,p')^{7}Li and neutron capture reactions. Gammas may Compton scatter in the detector and masquerade as fast neutrons. This background can be minimized by detector segmentation to reduce pile-up, and the use of materials with good pulse-shape discrimination properties.

IV. EXPECTED SIGNAL

The cargo types that are most suitable to our interrogation method are composed of non-hydrogenous materials. Incident epithermal neutrons suffer only slight energy losses via elastic scattering which dominates the total cross section. Outgoing fast fission neutrons are down-scattered mostly by inelastic collisions at energies above the (n,n') reaction threshold (typically around 1 MeV), and less efficient elastic collisions below it. In hydrogenous materials by contrast, both epithermal and fast neutrons are efficiently thermalized by elastic collisions with protons and tend to be captured.

We performed a MCNP5 simulation of the neutron return signal from a 10 kg ball of ^{235}U shielded by various cargos. The container was modeled as a box, 2.5 m by 2.5 m by 6 m, filled uniformly with material of density 0.4 g/cm^3. The generator was at 1 m from the box and pointing toward the uranium ball at the center. Table 2 shows the dramatic dependence of the return signal on the amount of hydrogen in the cargo. Adding a strong neutron absorber such as boron to the hydrogen further decreases the signal, but has little effect in non-hydrogenous materials.

TABLE 2
CALCULATED FAST NEUTRON SIGNAL FROM A 10-KG BALL OF ^{235}U EMBEDDED IN VARIOUS UNIFORM SHIELDING

Cargo Material	Number of fission neutrons per source neutron	Number of escaping fast neutrons (E > 1 MeV) into 4π per source neutron
H_2O	2×10^{-7}	1×10^{-10}
CH_2, borated 5 % by weight	$< 2\times10^{-10}$	$< 6\times10^{-14}$
Plywood (48 % H, 31 % C, 21 % O atomic fractions)	3×10^{-5}	1×10^{-7}
Al	2×10^{-3}	5×10^{-4}
Fe	2×10^{-3}	1×10^{-3}
Pb	2×10^{-3}	1×10^{-3}

V. DETECTOR HARDWARE

Our fast neutron detector consists of 96 cylindrical cells of xylene (Eljen EJ-301) scintillator with a total active area of 1 m. Each cell (10 cm in diameter, 7.6 cm long) is viewed by a single phototube (Photonis XP53X2). The amplified signals are passed to both a digital (Struck VME) and an analog (Mesytec MPD-4) data acquisition system, which output decay time and total energy of each event for later analysis. Neutron and gammas events generally have different light decay curves that become more separated with increasing energy. We used a threshold of 80 keV of electron-equivalent energy, corresponding to a proton recoil energy of ~ 700 keV in xylene [9]. For these parameters, we estimate the gamma rejection factor to be of order 10^{-3}. Stilbene crystals were also considered for this project. They have superior particle discrimination properties, but are currently not available in large quantities.

VI. EXPERIMENTS

We conducted a series of experiments with 370 g of ^{235}U placed in various cargos. The configurations were a pallet of steel pipes ($\langle\rho\rangle$ = 1.5 g/cm^3), a 60 cm thick steel

casement (ρ = 7.9 g/cm^3), and a pallet of plywood ((ρ = 0.55 g/cm^3). The neutron generator and the detector array were positioned on opposite sides of the test object. The plywood stack was approximately 120 cm thick, while the steel pipe stack was up to twice as thick. The position of the SNM sample in the plywood and steel pipe cargos was variable. The steel casement had a 10 cm void for placement of the SNM. The number of fast neutron counts for a 5 min. measurement time was typically 1000-2500 un-gated and about half that with the uncorrelated background removed.

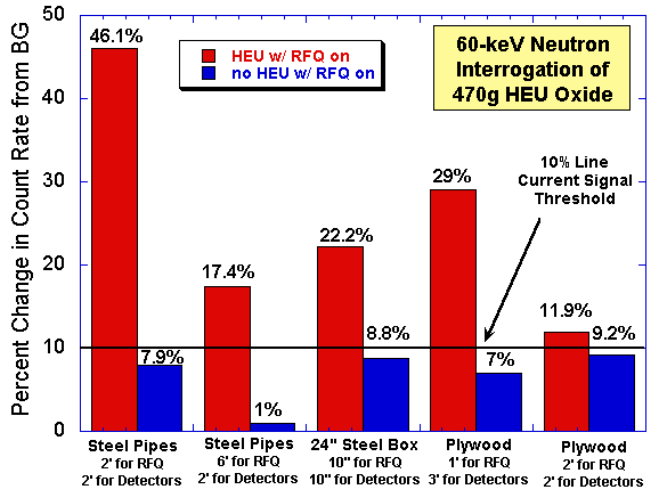

Figure 2: Results from all five measurements. The measurement time was 5 min each with a neutron generator rate of 5× 10^6/s.

Fig. 2 shows the preliminary results of our measurements. Using the tail of the time evolution plot to obtain a background count rate (cargo with 60-keV neutrons off), the presence of HEU can be detected in all five cases when a threshold of change between pulse on and tail count rates differ by 10 % or more. Clearly, the detection of the HEU sample in plywood becomes marginal for thicknesses exceeding 30 g/cm^2, whereas it is still relatively straightforward to penetrate 200 g/cm^2 of steel.

VII. Conclusion

We have developed and tested a shielded SNM detection technique that produces a clear positive signal in the presence of small quantities of ^{235}U. It is most suitable for thick and dense non-hydrogenous shielding. It is prompt and low dose, making it superior to methods involving the detection of delayed neutrons. It fails in scenarios where thick hydrogenous shielding is present. Other screening methods, such as measuring neutron or photon induced delayed gamma emission from fission products [10], would be more suitable in those cases.

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